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High-Power Transportable VLF Transmitter Facility

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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A 100-kW, transportable, very-low-frequency (TVLF) transmitter facility has been used for magnetospheric wave-injection experiments from sites in Alaska, New Zealand and Norway. A unique feature of the TVLF facility is the antenna which is a conducting cable lofted to an altitude of 1000 m by a 1000 m^3 helium balloon. The antenna is driven at its base as a monopole above a ground plane. The antenna cable also serves as the balloon tether. The lowest operating frequency in this configuration is 6.6 kHz at which the

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radiated power is 100 W. At the highest operating frequency used in the experiments, 21 kHz, the radiated power is 10 kW. In Norway power lines were used as antennas. The minimum operating frequency was then 1 kHz and the radiated power is estimated to be about 0.5 W. In this report we describe the components and performance of the TVLF facility as used for these magnetospheric experiments.

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sity of Sheffield, who was able to inspire a number of agencies to help us financially, and in addition, made the ground calibration measurements for the 1980 campaign. We wish to thank Prof. M. Garnier, G. Girolomi and J. Conrad, University of Paris, who made measurements and transmissions which were helpful in designing components for the larger transmitter, and demonstrated a transmission line configuration that would not cause telephone interference.

Dick Robbins, Bob Walter, Glen Jameson and Gordon Tolbert worked hard in the field to overcome a number of equipment failures and keep the transmitter on the air.

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I. INTRODUCTION

A 100-kW, transportable, very-low-frequency (TVLF) transmitter has been used by The Aerospace Corporation at sites in Alaska, New Zealand and Norway to perform VLF magnetospheric wave-injection experiments. The transmitter system can be used for research in VLF communications, navigation and geophysical exploration. In this report we describe the transmitter facility and the tethered balloon and power line antennas that have been used in the magnetospheric wave-injection experiments.

The transmitter system, designated AN/MRC-99(XN-1), was developed by the United States Navy during the 1960's. A unique feature of the TVLF facility is the antenna used in Alaska and New Zealand. This antenna was a conducting cable lofted to an altitude of 1500 m by a 1000 m^3 helium balloon. The antenna cable also serves as the balloon tether.

The antenna is driven at its base by a class AB power amplifier capable of providing 100 kW at continuous power to a matched load. At the frequencies utilized for the conjugate experiments the antenna is much shorter than one-quarter wavelength. The radiated power is usually limited by the voltage rating of the antenna system. At the lowest operating frequency, 6.6 kHz, the radiated power was 100 W. At the highest operating frequency, 21 kHz, the radiated power was 10 kW.

The original Navy system used a V-shaped, lighter-than-air (LTA) vehicle to lift and support the antenna/tether cable. Depending upon ambient conditions, the LTA vehicle was designed to support the antenna/tether at altitudes between 1500 and 3000 m and to maintain a relatively stable flight attitude in strong winds.

Due to funding limitations free-form balloons designed to support the antenna/tether at altitudes between 1250 and 1500 m were used during the 1972, 1973 and 1976 operations by The Aerospace Corporation. The free-form shape of the balloons limited operations to winds below 25 knots.

The original tuning system designed to tune the longer antenna to frequencies between 18 kHz and 30 kHz was no longer available. A new 90-mH inductor capable of tuning the shorter antenna to frequencies as low as 6.6 kHz was constructed for the magnetospheric transmission experiments. Within the band determined by the tuning system simultaneous transmission of multiple frequencies is possible and has been used for micropulsation generation studies.

The VLF receivers were located on the ground in the magnetic conjugate region and aboard the ISIS 2 and S3-3 satellites.

In the transmission experiments from Norway several power transmission lines were used as antennas. The VLF receivers were located on the U.S. Air Force P78-2 (SCATHA) satellite and the ESA GEOS-2 satellite. Here the lowest operating frequency was 1.28 kHz and the radiated power was ~ 0.5 W. The power lines were shorter than one-quarter wavelength. Capacitive and inductive tuning were used for short circuit and open circuit terminations to the ground respectively.

The system configurations described in this report are those used by The Aerospace Corporation for its magnetospheric transmission experiments.

II. HISTORY

In 1971 The Aerospace Corporation was contracted by the Naval Air Systems Command to perform magnetospheric propagation measurements at VLF. The primary objective was to measure the amplification properties of the plasma medium. The original proposal called for the assembling of a low-power transmitter facility from readily available commercial components.

Shortly after work began on the project, the TVLF facility was discovered and it was learned that the Navy had placed the system on the surplus list. The components had already been dispersed around the United States.

The original TVLF facility was housed in six trailers and thus had the capability of high-speed travel on major highways and the ability to negotiate secondary roads. The caravan included a transmitter/control trailer, an antenna tuning and matching trailer, a primary power trailer, a main winch trailer, a headquarters and maintenance trailer, a fuel truck, a utility vehicle and four helium tankers.

The primary power trailer and the transmitter/control trailer were made available to The Aerospace Corporation by arrangement with the Naval Electronics Laboratory Center in San Diego. The main winch trailer was located in Alabama and was obtained through the DCAS Office in Birmingham, Alabama. The headquarters maintenance trailer was also located in Alabama. Although it was not available for use, critical facility items were retrieved from the van. The antenna tuning and matching trailer had been incorporated into the Omega navigation station in Norway following a fire at that station. The major items which thus had to be obtained to utilize the facility were a new tuning system and a method of lofting the antenna.

During the winter and early spring of 1971 the components of the system were brought together at El Segundo, California where the necessary repairs and refurbishment were completed. In May 1972 the system was transported to Fort Irwin, California where comprehensive system level tests were planned.

Arrangements were made with the Navy to utilize a CH-3A helicopter from NAS Pt. Mugu to loft the antenna. Unfortunately the low atmospheric pressure at the ground level of Ft. Irwin (1200 m above sea level) along with high ambient temperatures prevented the helicopter from rising vertically above its "ground effect" altitude. The tests demonstrated that the antenna winch would operate satisfactorily. Electrical tests with the winch serving as a capacitive load also demonstrated that the power amplifier and tuning system were functioning properly.

Because the helicopter tests were unsatisfactory it was decided to use a helium balloon to loft the antenna. Although the winch is capable of holding 3350 m of antenna cable the available funds were only sufficient to purchase two balloons each capable of lofting the antenna to an altitude of 1525 m above the winch.

The first magnetospheric transmission experiments were conducted in August 1972 from Port Heiden, Alaska located at 56° 58' N, 158° 39' W. In June 1972 the equipment was shipped by rail to Seattle, Washington. There it was placed on a large barge and transported to Dutch Harbor, Alaska. At Dutch Harbor it was transferred to a second barge and finally was brought ashore on the beach at Port Heiden. Four nights of transmission were achieved with earth-ionosphere waveguide signals received at Palo Alto and El Segundo, California and Boulder, Colorado. Both magnetospheric and earth-ionosphere waveguide signals were received in the conjugate region at Dunedin, New Zealand.

High winds caused the destruction of both balloons on the ground after two nights of operation each.

In June of 1973 the TVLF system and two new balloons were shipped to Fort Richardson, Alaska. The transmitter was successfully operated from a site within a restricted air space located at 61° 21' N, 149° 38' W for approximately 200 hours between August 1 and September 14, 1973. VLF data were received at Dunedin, New Zealand, at Campbell Island and by the ISIS 2 satellite.

A clearing in Naseby State Forest, Naseby, New Zealand was used as the transmitter site for the 1976 experiments. The site is located at 44° 54' S, 170° 06' E. The transmitter was operated on 19 days beginning on June 15, and ending August 4, 1976. In all 117 hours of operation were logged.

Because the site was 750 m above sea level the net lift of the helium in the balloon supporting the antenna was reduced from that available at the Alaskan sites in 1972 and 1973. Only 1000 m of cable could be deployed at Naseby as compared with 1250 to 1500 m at Fort Richardson in 1973.

In 1976 scientists from several European countries expressed an interest in using the TVLF transmitter to transmit ELF signals to the European Space Agency satellite GEOS at synchronous orbit.

Because the signals had to be transmitted from North Norway where severe weather was anticipated and because the frequency required was a factor of three below the tuning capability of the balloon antenna hardware, it was decided to use a power transmission line as the antenna.

A 21.3-km long power line that normally carries 60 kV of three-phase power on the island of Andoya near the town of Andenes, Norway was chosen for the first transmissions. Since The Aerospace Corporation also provided a VLF

receiver for the P78-2 (SCATHA) satellite this provided a unique opportunity to study wave-particle interactions and whistler-mode propagation in the outer magnetosphere.

In the fall of 1977 Prof. M. Garnier of the University of Paris and Mr. M. Dazey of The Aerospace Corporation made impedance measurements on the Andoya line (Ref. 1).

Prof. Garnier attempted transmissions to GEOS using a 1-kW transmitter and the Andoya line. Problems with a backup line caused the power company to suggest an alternate line, the Sortland line. This line ran about 34 km between the towns of Strand and Konstadbotn. It was a "standby" line that was only required when it was necessary to service an operating line. Impedance measurements were performed on this line in September 1978 (Ref. 2). Test transmissions with the TVLF transmitter were begun on 27 September 1978.

A line near Kafjorddalen, Norway (69° 24' N, 21° 00' E) was tested by Prof. Garnier in the spring of 1979. After an electrical configuration change the telephone interference in the area was acceptably low and transmission experiments to SCATHA and GEOS 2 were conducted several times throughout 1979 and 1980.

III. TVLF TRANSMITTER FACILITY

Figure 1 is a photograph of the balloon system at the field site at Fort Richardson, Alaska. Figure 2 is a photograph of the system set up to use the power line at Kafjord, Norway. The components of the TVLF transmitter facility are identified diagrammatically in Figure 3. The elements of the system are described below in order from the primary power source to the balloon lofted or power line antenna.

Primary Power. Generation, control, and distribution of primary power at 440 V a.c. and secondary power at 208/120 V a.c., 60 Hz, for the TVLF system and high voltage d.c. anode power for operation of the power amplifier originates in the primary power trailer. Three Allis Chalmers type 21000 diesel engine generator sets, two operating in parallel and one as standby, supply the power inputs to the distribution panels. The rated output of each generator is 100 KVA at 440 V 3 phase. A 20-kW resistive load bank was installed in order to properly load the generators when major parts of the TVLF system were not operating. The high-voltage d.c. anode supply includes an oil-to-air heat exchanger. This supply provides 14,000 V d.c. when delivering 150 kW to the output tubes.

Intermediate Voltage Amplifier. The intermediate voltage amplifier (IVA) is a rack-mounted unit located in the transmitter control trailer. The IVA is a broadband, vacuum-tube amplifier. It receives low voltage signals from a frequency synthesizer and supplies a push-pull output signal between 1 and 30 kHz for amplification by the power amplifier.

Frequency Synthesizer and Programmer. The IVA was driven by a low voltage, highly stable, frequency synthesizer. Frequency stability is provided

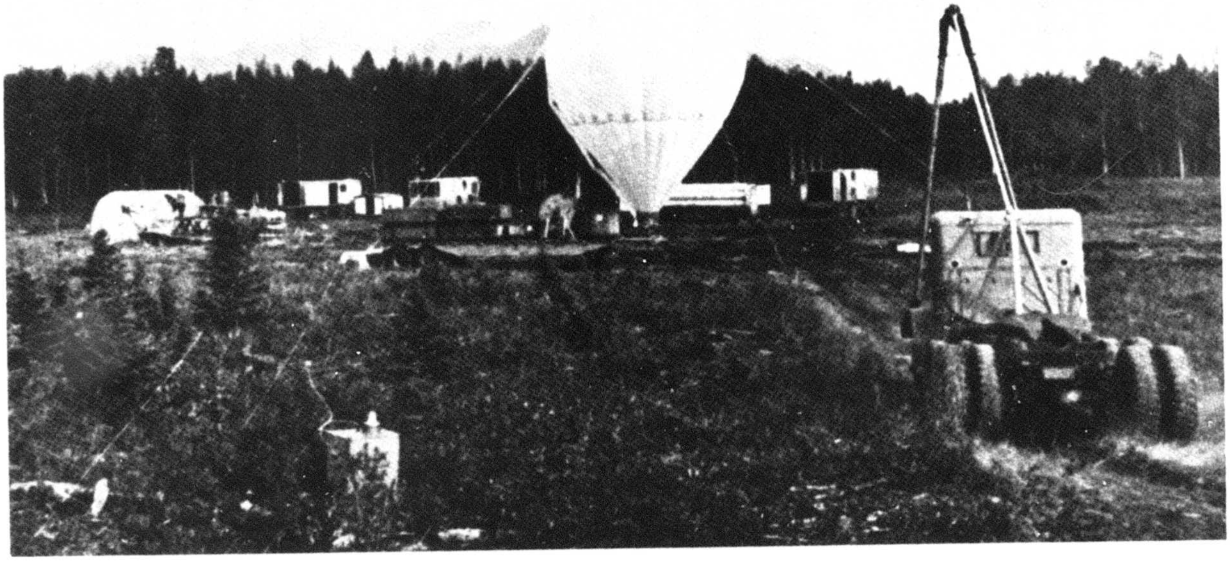

Figure 1. Photograph of the transportable VLF transmitter facility configured for operations with the balloon lofted antenna at Fort Richardson, Alaska.

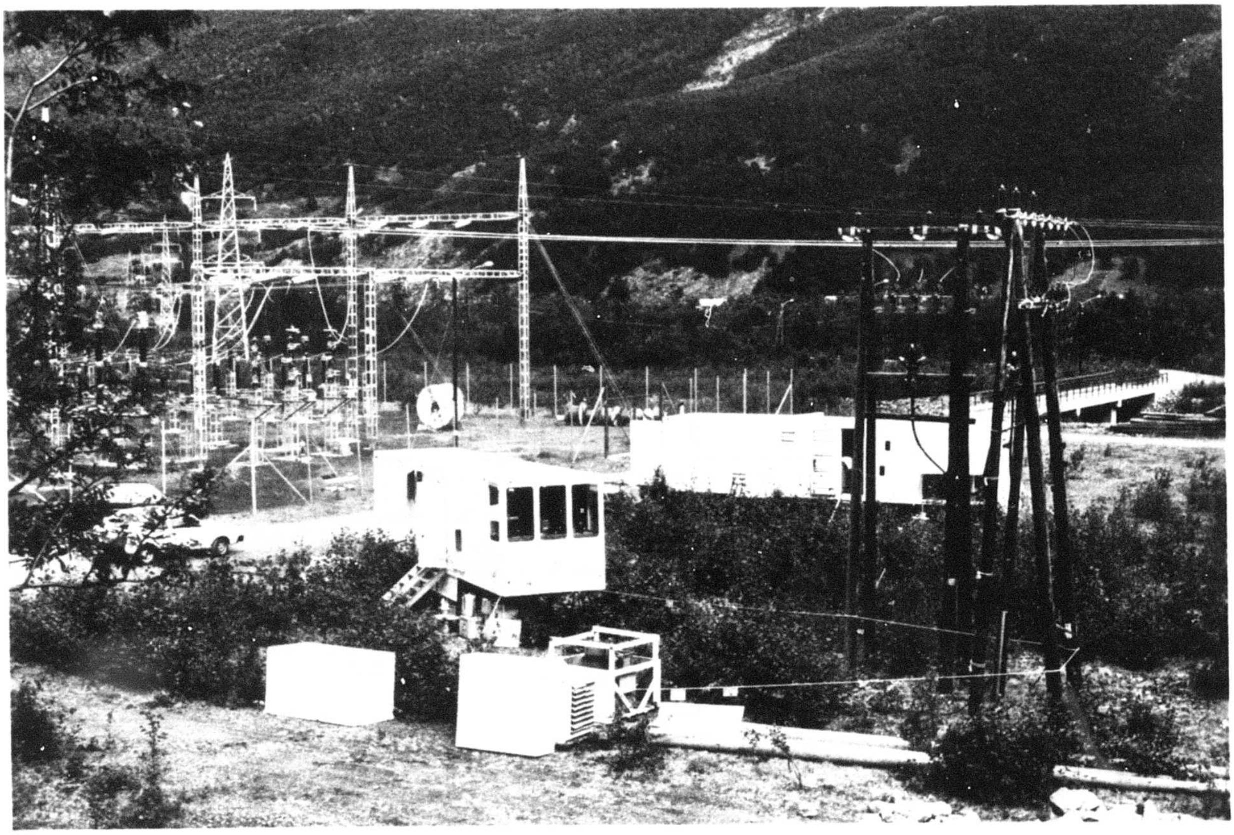

Figure 2. Photograph of the transportable VLF transmitter facility configured for operations with a power line antenna at Kafjorddalen, Norway.

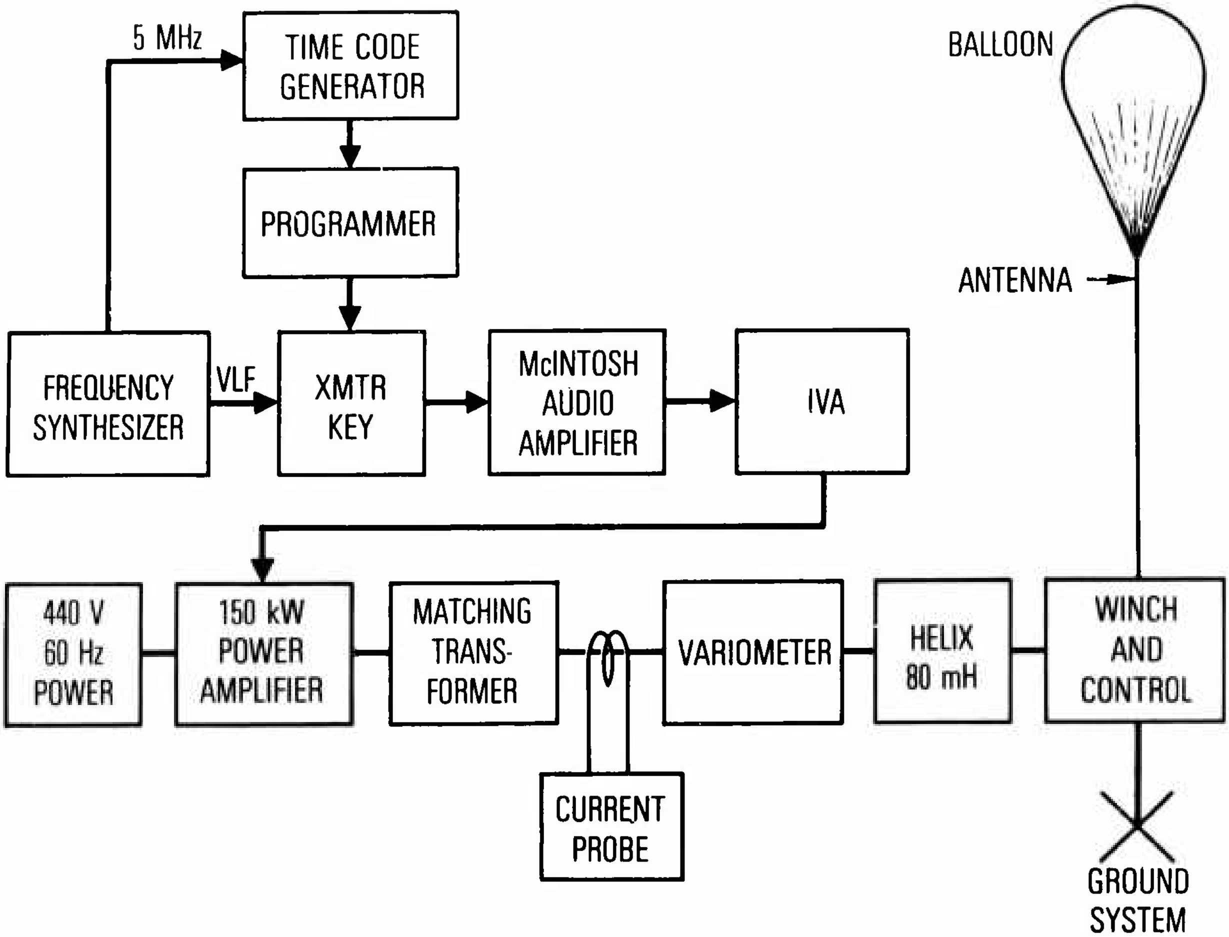

Figure 3. Block diagram of the transportable VLF transmitter facility.

by a 5 MHz quartz crystal oscillator in the frequency synthesizer. The stability of this oscillator is ± 1 part in 10^8 per day. A 1 MHz signal derived from the 5 MHz oscillator also drives a time-code generator. The time-code generator is set within ± 2 ms of Universal Time by synchronization with a 1 pulse-per-second output with the second marks transmitted by a time standard station such as WWV. Proper account was taken of the propagation delay from the time standard station to the TVLF site.

The transmitted program was provided by a multifunction unit (MFU) provided for the project by Prof. Dowden of the University of Otago, New Zealand. The MFU included a binary clock, a digital sweep, a SSB mixer, a pulse sequence programmer, a phase inverter and a provision to FSK between two frequency synthesizer sources.

An assortment of modulation programs were developed to satisfy a variety of scientific objectives. Among these programs are: (1) a repetitive pulse mode with the pulse repetition rate variable from 1/32 s to 60 s and the pulse length variable from 1/64 s to 30 s, (2) twelve preselected pulse sequences, (3) sweep-frequency mode, (4) phase reversal mode, and (5) continuous wave. All of these programs are synchronized to Coordinated Universal Time (UTC).

Power Amplifier. After receiving the input signal from the IVA, the four air-cooled EIMAC 4CX35000C tubes comprising the power amplifier linearly amplify the signal. Essentially, the power amplifier is a class AB high gain, wide-band amplifier capable of producing 100 kW and somewhat lower power output at lower frequency. Permanent installation of the power amplifier is in the rear compartment of the transmitter control trailer.

Filters are provided to eliminate parasitic oscillations. Interlocks and protection devices are liberally and significantly distributed to protect

personnel and prevent equipment damage caused by overloads, excessive heating, and lightning surges. Metering of all critical and adjustable circuits are provided on the transmitter meter panel located within the front compartment of the transmitter control trailer.

Output Transformer. The amplified RF signal obtained from the parallel push-pull (class AB) circuit of the power amplifier is coupled to the primary of the output transformer. The output transformer is mounted within the same enclosure as the power amplifier. The output transformer matches the high impedance of the power amplifier plate circuits to the 300-ohm impedance of the output line. A feedback signal to the intermediate voltage amplifier is obtained by electrically tapping one side of the secondary winding of the output transformer.

Secondary Power Supplies. Five rack-mounted power supplies in the forward and center enclosures of the transmitter control trailer provide the operating voltages for the intermediate voltage amplifier and power amplifier. These identical power supplies produce regulated low voltage potentials for the intermediate voltage amplifier grid bias and screen voltages, and power amplifier grid bias voltage. All of the low voltage power supplies operate from the single-phase source providing regulated output potentials that are adjustable at the rear of each unit. The two remaining power supplies are also identical and produce the required medium voltages for the intermediate voltage amplifier plates and the power amplifier screen grids. Operating from a three-phase source, the two medium voltage power supplies provide the positive 1200 V d.c. to the intermediate voltage amplifier plates and positive 1600 V to the screen grids of the power amplifier tubes.

Control of the transmitter, IVA and power amplifier circuits are accomplished from a control console and monitored at a meter panel mounted in the front of the transmitter control trailer. The controls located on the panel include interlock checking, filament on-off, high voltage off, blowers on-off, and metering of all circuits that are critical or require adjustment.

Matching Transformer. The antenna matching transformer is an autotransformer capable of matching the constant output coaxial cable impedance from the output transformer to the variable impedance presented by the antenna. The antenna impedance is a function of frequency, antenna length and configuration. The transformer impedance is changed by selecting one of nine output taps, which are remotely-controlled from the transmitter control console within the front compartment of the transmitter control trailer. The transformer employs an oil-to-air heat exchanger for cooling and maintains a flat frequency response through a 10 Hz to 100 kHz range.

Dummy Load. The dummy load is a 30-ohm, 150-kW, fan-cooled resistor with an insulation rating of 3000 V. The dummy load makes it possible to test all elements of the system from the diesel engine generators to the output, current-metering system without erecting the tuning system and deploying the antenna. The inductance of the dummy load is less than 20 μH and the absolute value of the impedance is within 5% of 30 ohms over the frequency range from 15 to 25 kHz.

IV. BALLOON ANTENNA SYSTEM

Tuning System. At VLF the balloon supported antenna is electrically short and has a large capacitive reactance. The antenna reactance is tuned by an inductance in order to match it to the system impedance. Course tuning is accomplished by tapping 10 individual coils which can be connected in series to achieve a maximum inductance of 90 mH, or may be interconnected in various combinations if less inductance is required.

The helix is fabricated from approximately 1/2 mi of 1/2-in. copper tubing wound in ten layers using Permali (wood impregnated with resin) for the spacers and structure. Surface arcs on Permali will cause carbon tracks, so safety gaps were provided which would arc before unsafe voltages could be applied.

Coarse tuning is performed manually by jumpers made from 0000 gauge welding wire and 100 ampere plugs recessed in corona rings. The mating plugs on the helix also have corona rings which were tested to 150 kV d.c. The helix settings are determined by calculating the capacitive reactance of the antenna, based on its height and the frequency, and then setting the helix to approximately the same inductive reactance.

Fine tuning is accomplished by a variable inductor referred to as the variometer. The variometer consists of two coils attached to a 3-ft. diameter by 6-ft. long, glass epoxy drum which is fixed, and two coils attached to a moving coaxial drum which is inside the fixed drum. The four coils are interconnected so that a 180° rotation of the inner drum causes the mutual inductance between the inner coils to go from full adding to full bucking. The maximum inductance of the variometer is 1.8 mH, the minimum is 0.8 mH.

Fine tuning is accomplished by maximizing the output current, observed on a current probe monitored at the control console while the variometer is rotated by a remotely-controlled motor.

The output of the matching transformer is connected to the input of the variometer. The output of the variometer is connected to the low potential point on the helix. The connections are made so that the top of the helix is at the highest potential. The top of the helix is connected to the winch by a 25-ft. length of 3/4-in. copper tubing.

Winch System. The trailer-mounted main winch shown in Figure 4 is designed for smooth and fast handling of the balloon antenna/tether cable during launch and retrieve operations. The winch trailer contains the takeup reel assembly, capstan assembly, fair lead and cable guides, the necessary gearing, motor-generator sets, d.c. drive motors, tension-sensing equipment and corona shielding. The normal reel-in and reel-out velocity is 65 m per minute.

A number of amplidynes and servo circuits are used to assure smooth operation in the two operational modes; constant velocity and constant tension. Brakes are used to prevent movement when the antenna is not being deployed or retrieved.

Most of the winch elements are mounted on a corona ring and frame which is itself mounted on eight Permali struts. The Permali insulators and the corona ring allow the potential of the antenna and most of the winch elements to be raised to 100 kV rms. The main drive motors are coupled to the capstan and the take-up drum by 4-in. diameter Permali shafts. A tension-measuring shaft fabricated from Permali is used to transmit the antenna cable tension to instrumentation circuits in the transmitter/control trailer. From the control

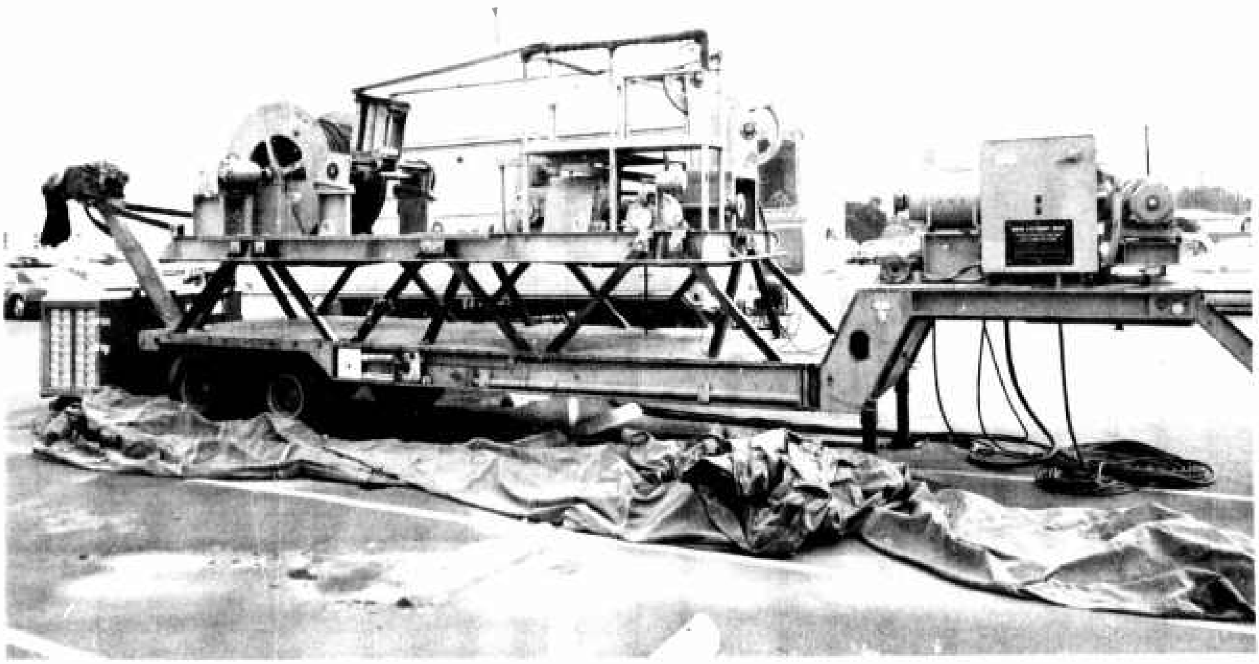

Figure 4. Photograph of the electrically insulated winch used to launch and retrieve the tethered balloon.

console the operator can control the deployment and retrieval in the constant tension and constant velocity modes.

The front of the transmitter/control trailer contains windows so that when the trailer is properly placed the operator has an unobstructed view of the winch during balloon launch and retrieve operations.

Ground System. A surface ground plane was installed to provide an adequate ground contact to insure safe electrical operating conditions and to increase the overall radiation efficiency of the antenna.

Bare copper wire (#4 AWG) was laid around the periphery of the launch/retrieve complex. Four equally spaced internal radials were connected between this wire and a central grounding stake located near the winch trailer at the center of the complex. In addition, 24 equally-spaced, bare, copper-wire (#12 AWG) radials were extended outward 165 m from the peripheral wire and staked by 3/8-in diameter copper-weld ground stakes at 85-m intervals.

Antenna Cable. The antenna cable shown in Figure 5 is stored on the takeup reel on the winch trailer. The 3350-m cable is composed of a corded acron core covered with a polyethylene jacket; and EC-0 aluminum electrical conductor spirally wound around the polyethylene jacket at an angle of 45°, and a polyethylene outer jacket. The nominal diameter of the cable is 1.8 cm. The nominal weight is 0.28 kg/m and the minimum breaking strength is 4500 kg.

A common figure of merit of balloon tethers is the 'hanging length', which is the weight-per-unit-length divided into the breaking strength. For the TVLF antenna this value is 16,000 m.

The d.c. resistance of the cable is 0.75 ohms per 100 m. An electrical connection is made to the winch structure by cutting away the polyethylene and

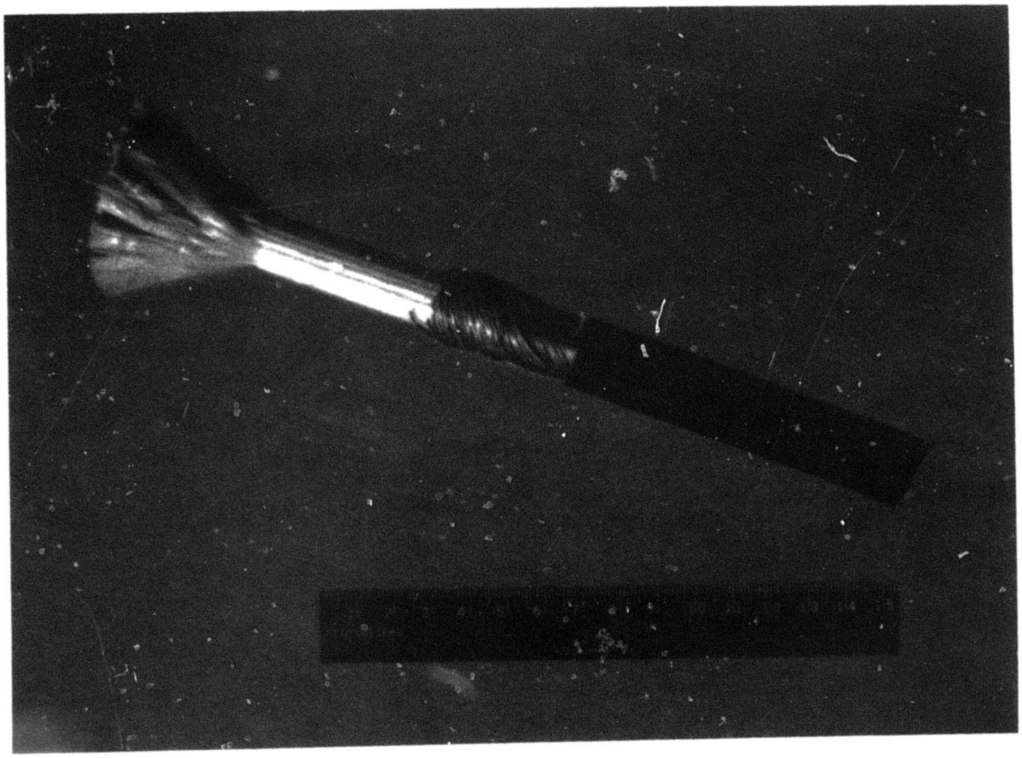

Figure 5. Photograph of the antenna cable with the outer jacket removed exposing the aluminum wire and Dacron core.

clamping the cable in a 10-cm long 'mousetrap' assembly which provides electrical continuity and releases from the cable when excess tension occurs.

Since the antenna is at high voltage it is terminated at the upper end by a corona ring, which is fabricated from 1-in. copper tubing. The corona assembly connects the antenna to a 9-m insulating link. The link is a section of antenna cable with conductors removed. The insulating link is connected to a swivel which attaches to the lifting eye of the balloon.

Balloon. The balloons were manufactured by RAVEN Industries, Inc. from heat-sealable, urethane-coated, nylon cloth. The volume of each balloon is 1000 m^3 and the maximum diameter is 12 m. The balloon and harness stands 16 m high. The balloon weighs approximately 82 kg. They were furnished with six handling lines, a destruct device and a bottom-fitting eyebolt attach point.

The balloon and antenna were successfully operated at a 1200-m altitude in winds of 15 to 20 knots.

Strobe lights operated by a 12-V car battery, RF command and an aneroid receiver switch for the destruct system were attached at the base of the balloon. The net lift at ground level was approximately 545 kg. The net lift at 1200 m was approximately 90 kg.

When not performing its antenna support function, the lifting eye is secured to an anchor point consisting of a 1.2 × 1.2 × 1.2 m concrete block buried in the earth, and the handling lines are secured to screw anchors.

When the antenna is lofted, the main lift force is transferred to a 3/4-in. nylon line attached to a 4-wheel-drive truck. The antenna insulating link is attached to the lifting eye, and the lifting force is placed on the 3/4-in. line by backing the truck away. The anchor point is then disconnected, and tension is carefully applied to the antenna by slowly moving the truck forward

toward the anchor point. When all of the lifting force is transferred, the antenna is winched in to the corona ring, the 3/4-in. line and handling lines are furled so that they will not come in contact with the corona ring.

Once the operating altitude is reached, the antenna connection to the winch is made as described previously, the helix is tuned, and transmission begins.

Electrical Parameters. The maximum voltage that may be applied to the winch is 100 kV r.m.s. Above that voltage corona, sparking, and local fires occur. When moisture condensed on the winch, arcing occasionally occurred along the Permali struts and at times it was necessary to operate at voltages considerably lower than 100 kV. The maximum base antenna current is limited to 100 A r.m.s. by heating at the "mousetrap", the connection between the antenna and the winch. Localized heating at this connection point could cause the dacron core to break, releasing the balloon. At the frequencies used for the magnetospheric transmission experiments typical operating currents were considerably less than 100 A and no "mousetrap" heating was detected. Typical operating conditions are listed in Table 1.

The characteristic impedance, Z_o, of the antenna is given by (Ref. 3);

$$Z_o = 60 \left[\ell n \left(\frac{h}{a}\right) - 1 \right] \tag{1}$$

where h is the height and a is the diameter of the antenna. For h = 1200 m and a = 0.19 cm, Z_o = 742 ohms.

The antenna reactance is capacitive and is given by:

$$X_c = Z_o \cot \frac{2\pi h}{\lambda} = 2104 \text{ ohms} \tag{2}$$

Table 1. Typical Operating Conditions
for the TVLF Balloon Antenna System

Parameter	Value
Frequency	13.275 kHz
Wavelength	22,600 meters
Antenna Base Current	40 amperes
Altitude	1220 meters

From the capacitive reactance we determine the winch voltage to be:

$$V = I\ X_c = 84{,}180\ \text{V} \tag{3}$$

the capacity to be:

$$C = \frac{1}{\omega X_c} = 5.700 \times 10^{-9}\text{F or } 5700\ \text{pF} \tag{4}$$

and the required helix inductance:

$$L = \frac{X_c}{\omega} = 0.025\ \text{H} \tag{5}$$

A suitable approximation for the cable capacitance for use in tuning the antenna circuit is:

$$C = 5\ \text{pF/m} \tag{6}$$

which gives 6000 pF for a 1200-m high antenna.

Radiated Power. The radiation resistance, R_r, of an antenna is related to the power radiated P_r by the expression:

$$P_r = I^2\ R_r \tag{7}$$

where I is the r.m.s. current at the base of the antenna.

The radiation resistance for an electrically short vertical antenna is given by Jasik (Ref. 3):

$$R_r = 415 \left(\frac{h}{\lambda}\right)^2 \text{ or } P_r = 415\, I^2 \left(\frac{h}{\lambda}\right)^2 \qquad (8)$$

It should be noted that the "standard" antenna used by Watt (Ref. 4) is a short vertical antenna of height h_e above a ground plane with uniform current flowing throughout its length. This is representative of an antenna with heavy top loading. The expression from Watt for radiation resistance is then:

$$R_r = 160\pi^2 \left(\frac{h_e}{\lambda}\right)^2 \qquad (9)$$

By convention, the "electrical height" of any antenna can be determined by knowing the radiation resistance and the above expression.

The current in a short antenna without top loading will decrease essentially linearly to zero at the top. The radiation resistance for such an antenna is:

$$R_r = 40\pi^2 \left(\frac{h}{\lambda}\right)^2 = 395 \left(\frac{h}{\lambda}\right)^2 \qquad (10)$$

The electrical height, as defined by Watt, of a vertical antenna as described by Jasik is then

$$h_e = (415/160\pi^2)^{1/2} \times h = 0.5125 \times h \qquad (11)$$

The apparent 2-1/2% discrepancy may be attributed to the fact that a vertical antenna of finite diameter will always appear to be slightly top loaded.

The current monitor in the TVLF system measures the sum of the antenna

base current and winch capacity current. The winch capacity causes a reduction of about 3.4 A in the antenna current for the example we are considering. The antenna current would then be 36.6 A.

Short Distance Field Measurements. The power radiated by a short antenna above a perfectly conducting ground plane is related to the electromagnetic field components (E and H) by (Ref. 4):

$$P_r = \frac{E^2 d^2}{90} = 160\pi^2 H^2 d^2 \tag{12}$$

During c.w. operations at a frequency of 13.275 kHz, the radiation field was measured as a function of distance from the antenna on two nights in September 1973. The measurements were made with a Singer Instrument EMC-10 spectrum analyzer using a calibrated loop antenna provided with the analyzer. The equivalent electric fields obtained on each night are plotted as a function of distance from the transmitter site in Figure 6. The radiated power obtained from the slope of these curves using Eq. (12) is 1400 W on September 7 and 940 W on September 8. Each night 1220 m of antenna cable were deployed and the r.m.s. current at the base of the antenna was 36.6 A. However, on the first night the wind was calm and the antenna was essentially vertical. From the measurements the effective height, which would ideally be equal to half the actual height, was determined to be 568 m. On the second night the wind was 20 to 25 knots and the blow down angle of the cable at the winch exceeded 45°. The effective height under these conditions was determined to be 465 m.

From these measurements the radiated power can be computed for other operating conditions. Figure 7 shows the expected radiated power as a function of frequency. The system in its present configuration can radiate in

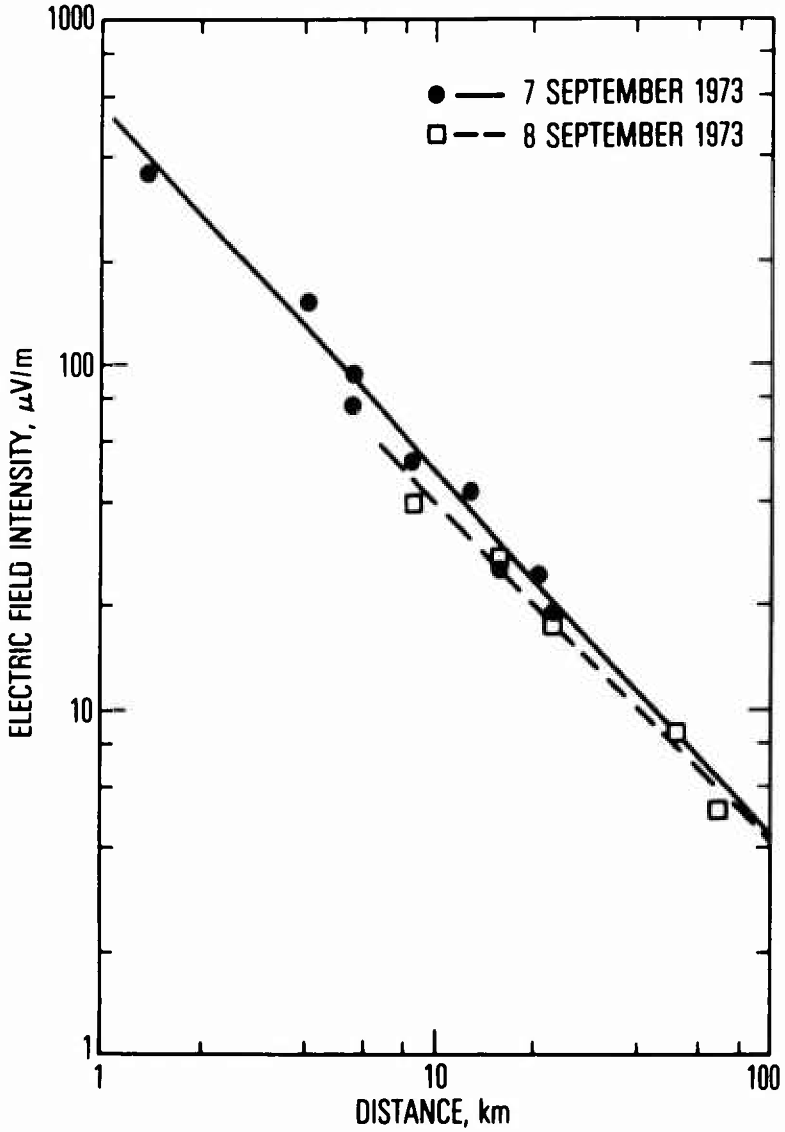

Figure 6. The electric field intensity as a function of distance from the balloon lofted antenna during operations at 13.275 kHz with a base current of 36.6 A.

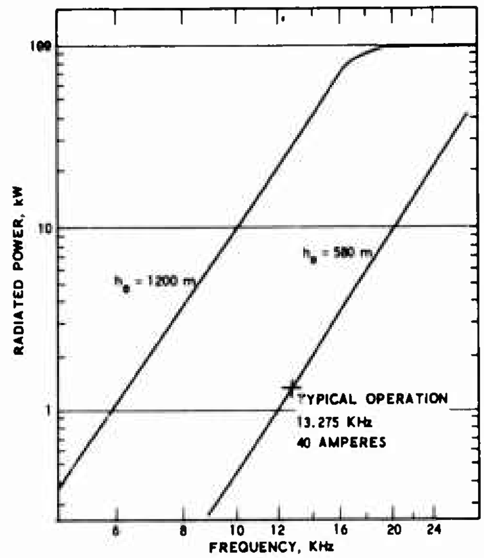

Figure 7. Power radiated by the TVLF antenna as a function of frequency for two effective antenna heights.

excess of 100 kW at frequencies greater than 20 kHz.

Long Distance Field Measurements. The field strength measured at El Segundo, California under typical operating conditions at 13.275 kHz was 160 μV/m.

The field strength measured at Dunedin, New Zealand due to the earth-ionosphere waveguide signal varied from 10 μV/m to 30 μV/m.

V. POWER LINE ANTENNA SYSTEM

Impedance measurements and radiation tests were conducted on three power lines in North Norway. These lines are referred to as the Andoya line, the Sortland line and the Kafjord line. Since the first two lines could not be used for the wave injection tests because of problems with a backup line and telephone interference we will limit our description here to the Kafjord line which was successfully used for a series of wave-injection experiments in 1979 and 1980.

The Kafjord line runs 14 km between Kafjorddalen and Lake Guolasjav'ri in Troms Province, North Norway. The line runs up a mountain from sea level to 800 m.

Initial radiation tests caused unacceptable interference at the telephone switchboard in Birtavarre near the Kafjorddalen end of the line. Since the residences were all close to the transmitter end of the line, a test was made with the first 3.6 km of the line 'floating' above ground. This test indicated that currents above 50 amperes could be used without causing telephone interference.

The Operating Mode of Transmission Line Antennas

In the simplest configuration, a transmission line antenna can be considered a rectangular loop antenna with current going out on the transmission line wires, returning to ground at the far end, and returning in the ground back to the low potential side of the transmitter (Ref. 5). When VLF currents travel in the ground they penetrate large distances because the skin depth is large at the low frequencies involved. In its simplest form the area of the loop antenna is approximately the product of the length of the transmission

line and the skin depth (at the frequency of interest) divided by the square root of two.

In the interest of safety and ease of design high-power transmitters are usually operated at high currents and relatively low voltages, which constitutes a low output impedance. A transmission line a quarter of a wavelength long with an open circuit at the far end provides a low impedance for a transmitter and is the preferred operating mode. Another advantage of a quarter-wave open-circuit antenna is that only one connection to the earth is necessary.

In general, when a transmission line is provided, the quarter-wave resonance does not occur at the desired transmission frequency. For transmissions to the SCATHA and GEOS satellites from North Norway the desired frequency was about 1300 Hz, based upon the expected electron gyrofrequency at the location of the spacecraft. We find the typical propagation velocity in transmission line antennas to be about 0.7 the speed of light for the lines measured in North Norway. The desired length of a transmission line for quarter-wave resonance is then 40 km.

As a practical matter, it is difficult to arrange the use of power transmission lines because of power company constraints, and the lines that have been made available are usually shorter than 40 km. The shorter lines may be electrically lengthened by adding the proper components.

In the 1979 campaign, the Kafjord line was lengthened by adding capacitors at the far end. There were severe voltage, frequency and current requirements for the capacitors, however, special units were obtained that functioned satisfactorily. The capacitor current had to be reinserted into earth, requiring a second grounding connection. The capacitor ground connec-

tion was made in inhospitable terrain and added considerable series resistance to the complete system.

In the 1980 campaign, a special inductor was constructed at the TVLF transmitter site and connected in series with the transmission line achieving the necessary reduction in resonant frequency with minimal increase of circuit resistance.

Details and performance results of the TVLF-antenna combination are described by Dazey and Koons (Ref. 6). The main results will be summarized here.

Electrical Characteristics of the Kafjord Line. Figure 8 illustrates schematically three of the Kafjord, Norway transmission-line antenna configurations. Note that in all three cases, 3.6 km of elevated line was used to transmit the power to the 10.6 km of line which was the actual antenna. Impedance measurements were made in all three configurations and estimates of inductance/meter, capacitance/meter, characteristic impedance, velocity of propagation, skin depth in the earth, and earth resistivity were made as a function of frequency.

Provisions were made by the power company to allow access to the line at the Kafjorddalen end, and to provide an open or short circuit termination upon request at the Lake Goulasjav'ri end. The basic data obtained in the measurements was the open and short circuit impedance (Z_{oc}, Z_{sc}) versus frequency over the range from 1 to 20 kHz. The measurement technique (Ref. 6) provides the modulus of the impedance, rather than the reactive and resistive terms, although at maxima and minima in the curves, one can assume the impedance is purely resistive. The skin depth varies significantly with frequency and this

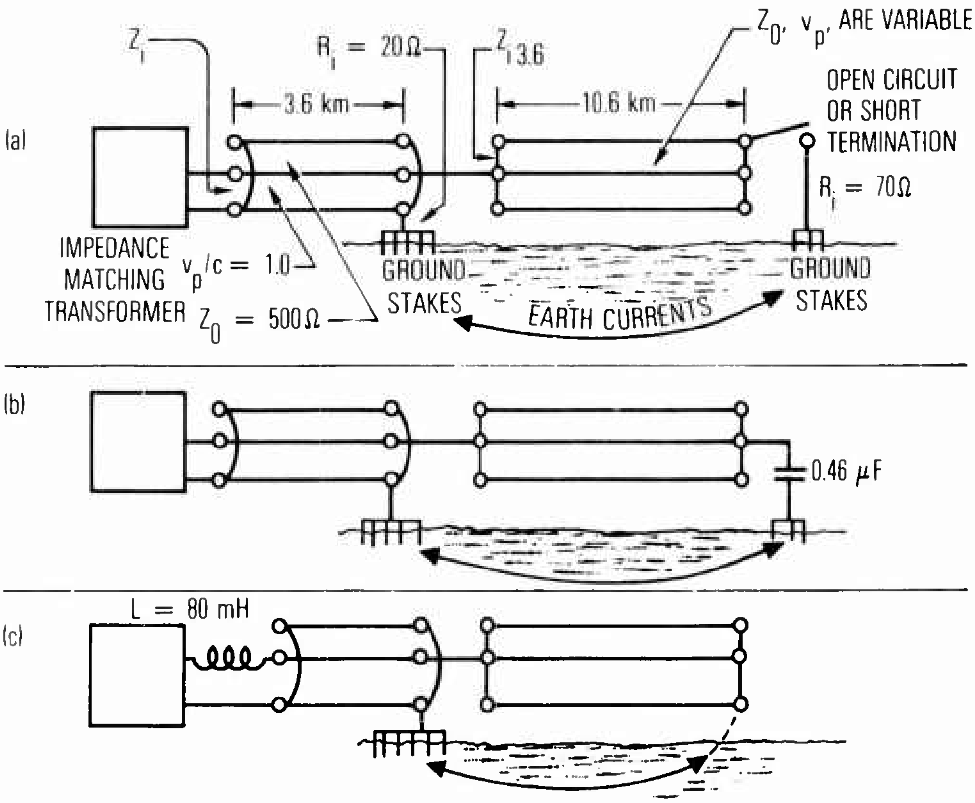

Figure 8. Kafjord, Norway transmission line antenna configurations. (a) Test configuration, resonant frequency = 3.8 kHz, (b) capacitive tuning, resonant frequency = 1.3 kHz, (c) inductive tuning, resonant frequency = 1.3 kHz.

causes significant changes in the characteristic impedance and the velocity of propagation.

Capacitive Tuning of the Kafjord Line

The Kafjord line resonated at 3.8 kHz in the quarter-wave open-circuit mode. Operational requirements made it necessary to operate at 1.3 kHz, and in 1979 this frequency was obtained by adding capacitors to the far end of the line.

Simple trigonometric expressions are usually adequate for estimating the value of the capacitance required and the expected losses. Based upon earlier measurements, it was assumed that the line would have a characteristic impedance of about 350 ohms.

The impedance of a short-circuit line, when measured at the open-circuit end is given by:

$$Z_{oc} = j\, Z_o \tan\theta \qquad (13)$$

where

$$\theta = \frac{360 \times 14{,}200 \times 1300}{3 \times 10^8 \times 0.7} = 31.6° \qquad (14)$$

Since the above value is inductive, the line can be 'tuned' with a capacitor with the same numerical value of reactance:

$$X_c = 350 \tan\theta = 215 \text{ ohms} \qquad (15)$$

or

$$C = \frac{1}{2\pi \times 1300 \times 215} = 5.6 \times 10^{-7} \text{ F} \tag{16}$$

Operating high voltage, high current capacitors at any other frequency than 60 Hz requires special considerations. It was possible to obtain capacitors with the standard loss factor rating, a series conductor resistance rating, and a wattage rating. From the specifications it was possible to determine an array of capacitors which could be used, although not at the maximum power desired. The capacitor specifications are given in Table 2. It was estimated that at 1.3 kHz, the total capacitor current would be 35 amperes for an input current of 40 amperes from the TVLF system. The total voltage at the capacitors would then be 8,000 volts.

Twenty capacitors were purchased and pairs were connected in series, then ten pairs were connected in parallel, so the voltage on each capacitor was divided in half and the current was divided by ten. The losses could then be calculated for each capacitor. The dielectric loss which is the power factor times the voltage times the current was 14 watts.

The conduction loss, which is the square of the current times the conductor resistance, was 3 watts, for a total of 17 watts. Since the capacitors were only rated for 10 watts, care was taken to operate at less than 60% duty cycle. The wattage rating is based on a 40° F temperature rise. The location of the capacitors on the top of a mountain where there was a steady cold breeze would probably have allowed up to 100% duty cycle without much danger of overheating.

The equivalent series resistance of the capacitors was $R = P/I^2 = 1.4$ ohms. The net resistance for the series-parallel array was about 0.3 ohms, which was negligible compared to the earth insertion resistance.

Table 2. Capacitors Used to Tune the Kafjord Line to 1.3 kHz

Parameter	Value
Capacitance	0.1 μF
Voltage rating	13.0 kV
Power factor	0.001
Conductor resistance	0.25 ohms
Power dissipation	10.0 watts
Total capacitance	0.56 μF

Figure 9 shows the impedance vs frequency curve with 0.46 μF capacitance. The minimum impedance at resonance, i.e., the total series resistance, is the parameter that determines the antenna current possible with a given amount of transmitter power. The allocation of resistance is shown in Table 3.

Since all the current in the line does not go through the capacitors, the apparent resistance is somewhat less than the 70 ohms determined as described in the previous section. The current which does not go through the capacitors is returned to the earth as displacement current along the length of the line.

Inductive Tuning of the Kafjord Line. If an inductor is placed between the transmitter and the transmission line, the resonant frequency will be reduced. If we take the same frequencies as in the previous section we may determine the value for this inductance.

The impedance of an open circuit line is given by:

$$Z_i = - Z_o \cot \theta = -350 \cot 31.6° = -569 \text{ ohms} \tag{17}$$

Since this is capacitative, this may be tuned by an inductance with the same reactance, and the value of the inductance is:

$$L = \frac{569}{2\pi \times 1300} = .070 \text{ Henrys} \tag{18}$$

Typical inductors have high losses at high frequency because the conductors are immersed in their own alternating magnetic field causing eddy current losses. The large equivalent series resistance may be reduced by using an 'open' construction at the expense of increasing the length, spacing and size

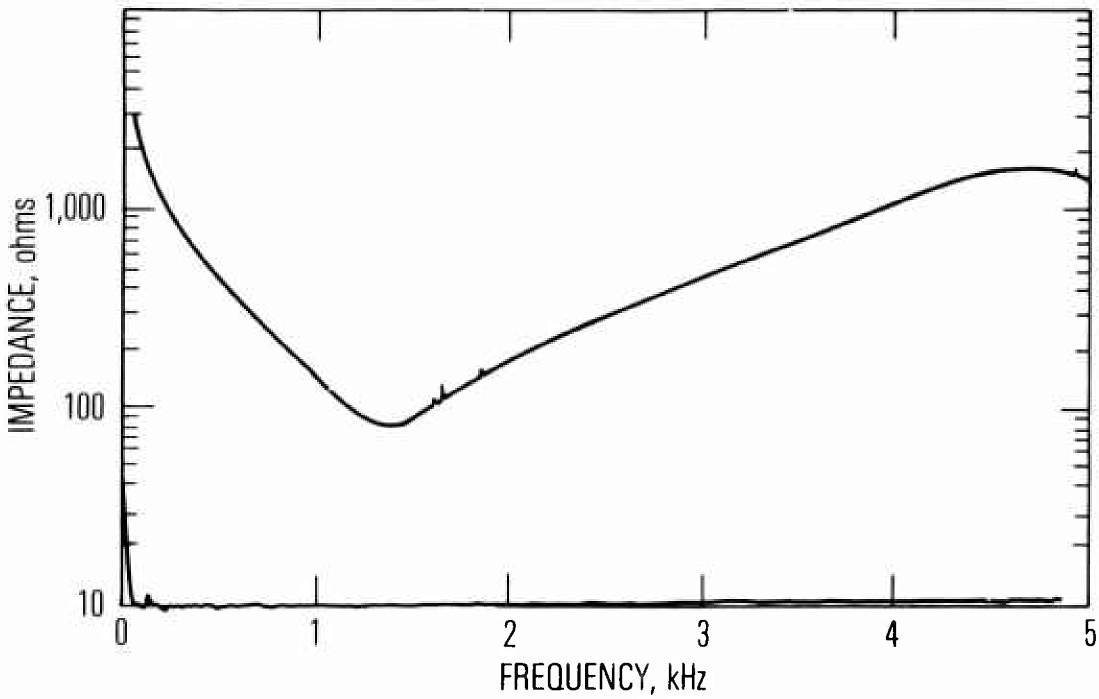

Figure 9. Impedance of the Kafjord line tuned by a 0.46 μF capacitance in series with the line to ground at the far end of the line from the transmitter.

Table 3. Allocation of Series Resistance in Kafjord Power Line Antenna

Insertion Resistance at 3.6 km	= 20 ohms
Ground Transmission Resistance	= 14 ohms
Insertion Resistance at Capacitors	= 50 ohms
Total	= 84 ohms

of the conductors. The final inductor design was based on formulas given by Grover (Ref. 7) and Terman (Ref. 8). The physical and measured electrical parameters of the inductor are given in Table 4. The measured results were within reasonable agreement with the calculated values.

A 50-ft. roll of soft copper tubing was sufficient for each layer. Tubes were soft soldered using a butt joint. Spacers were glass melamine. Assemblies of 12 layers were fabricated at El Segundo and shipped by air to Tromsoe for final assembly of the full 120 layers at the site of the TVLF transmitter.

Figure 10 shows the impedance curves of the line, the inductor, and the line with the inductor installed.

Note that the series resistance was lowered to 45 ohms with inductive tuning, as compared to 84 ohms with capacitive tuning, allowing currents as high as 47 amperes for the 100-kW transmitter.

Comparison of Measurements With Model Impedances

Barr (Ref. 9) has presented a computational method for the evaluation of the characteristic impedance, propagation constant and open- and short-circuit input impedances of an assembly of N, parallel, lossy conductors of circular cross section above an imperfectly conducting ground plane.

We have evaluated Barr's model for the electrical properties of the Kafjord line given in Table 5. The impedance of the antenna was transformed to the impedance at the transmitter site where the impedance was measured by assuming that the 3.6-km section operated as a transmission line (see Fig. 8) had a characteristic impedance Z_0 of 500 ohms and a phase angle at the antenna given by $\theta = 4.62 \times 10^{-3} \times f$ deg where f is the signal frequency.

Table 4. Inductor Used to Tune the Kafjord Line to 1280 Hz

Parameter	Value
Turns	600
Turns/layer	5
Outside diameter	36 inches
Height	120 inches
Horizontal turn spacing	1 inch
Layer spacing	1 inch
Conductor diameter	0.25 inches
Inductance	0.078 Henrys
Resonant bandwidth	15.4 Hertz
Q	82.8
Series Resistance	7.5 ohms

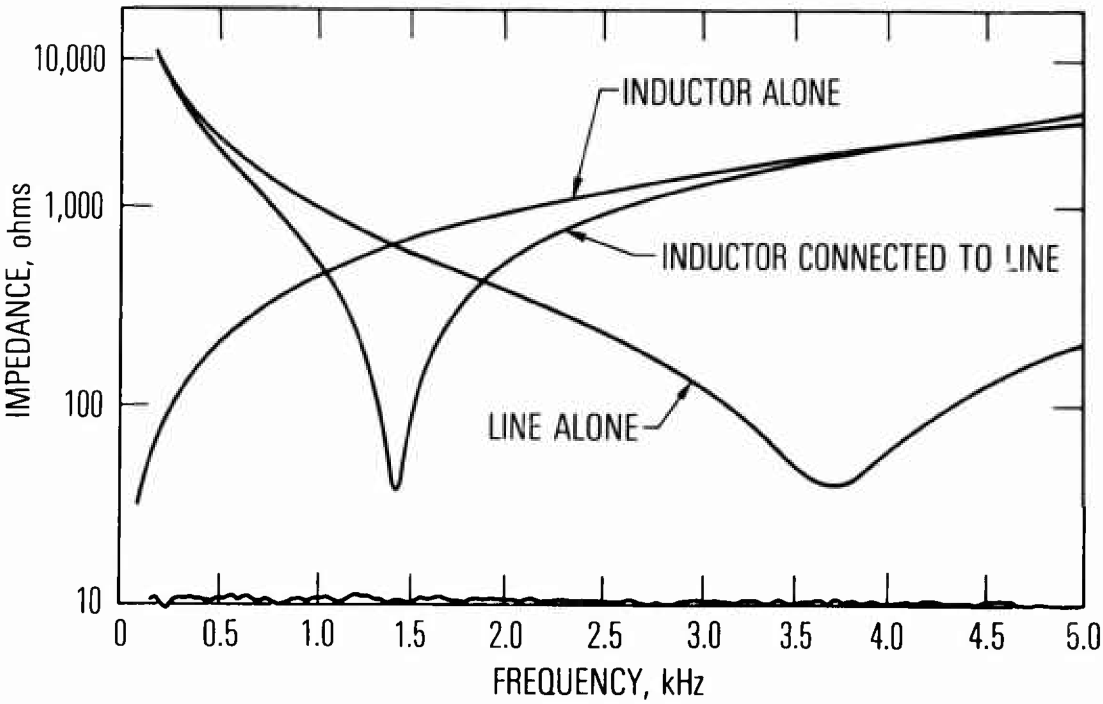

Figure 10. Impedance of the Kafjord line in the indicated configurations.

Table 5. Electrical Properties of the Kafjord Line at 1280 Hz

Parameter	Value
Wire diameter	0.0087 meters
Wire spacing	1.5 meters
Characteristic impedance	417 ohms
Velocity of propagation	0.681 c
Dielectric constant	2.16

The open- and short-circuit impedances were computed for ground conductivities ranging from 10^{-4} to 5×10^{-3} S/m. The most sensitive parameter for a comparison of these model calculations with the measured impedance is the frequency of the first minimum in the open-circuit impedance. In 1979 and 1980 six impedance curves were plotted in this configuration. The average value of the frequency of the first minimum is 3729 ± 62 Hz. This frequency corresponds with a ground conductivity of 3×10^{-4} S/m. Impedance values computed from the model are plotted with the experimental curve in Fig. 11.

Radiated Power

Magnetic induction measurements were made by University of Sheffield personnel at Lavangsdalen, Norway and Kiruna, Sweden during the 1980 campaign. The measurements at Kiruna, a distance of 165 km from Kafjord, were used to estimate the radiated power, P_{rad}, using expressions from Bernstein et al. (Ref. 10).

At the time when r.m.s. antenna current was 45 A the magnetic induction, $B_\phi = \mu_o, H_\phi$, measured near Kiruna, Sweden was 3.1×10^{-14} T (L. Woolliscroft, private communication).

At 1280 Hz the signal is strongly attenuated in the earth-ionosphere waveguide. We adopt an attenuation of 30 dB/Mm or 3.5×10^{-6} nepers/m from Figure 3 of Reference 10.

The values in Table 6 then give a radiated power of 0.168 W. The earth's conductivity calculated using this value for the radiated power and the line parameters in Table 5 is then 1.4×10^{-3} S/m. This value is a factor of 4.7 higher than that obtained from the line impedance measurements described in the previous section. Since both results are model dependent this discrepancy

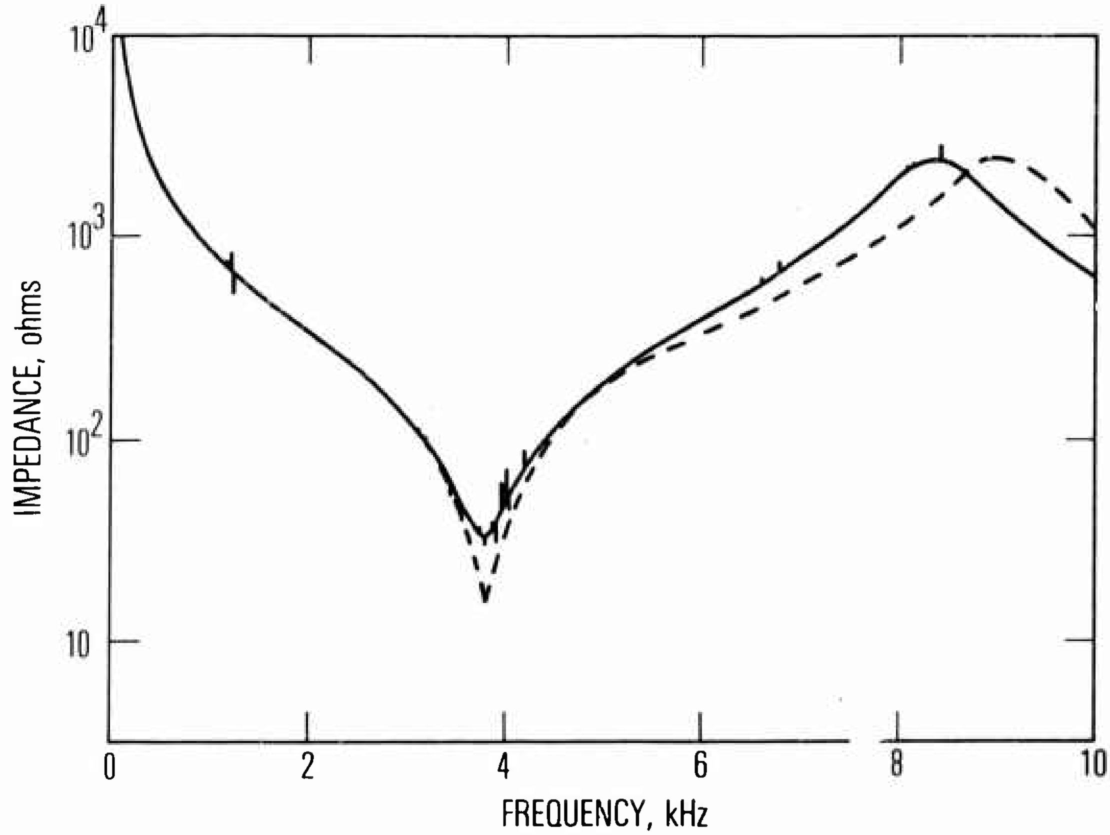

Figure 11. A comparison of the measured open-circuit impedance of the Kafjord line (solid curve) with the open-circuit impedance computed using Barr's program (dashed curve).

Table 6. Parameters Used to Compute the Radiation Resistance of the Kafjord Antenna at 1280 Hz

Parameter	Value
Skin depth	4,860 meters
Line length	11,600 meters
Ionospheric height	80,000 meters
Wavelength	234,000 meters

is not surprising. The radiated power computed using the lower conductivity obtained from the impedance measurements is 0.79 W. This is probably an upper bound with the actual value closer to the 0.17 W obtained from the magnetic induction measurements.

VI. SUMMARY OF SATELLITE RADIATION MEASUREMENTS

Transmissions from the mid-latitude sites at Port Heiden and Fort Richardson Alaska and Naseby, New Zealand were routinely detected by VLF receivers aboard the ISIS-2 and S3-3 spacecraft. Spectrograms of VLF signals received by ISIS-2 satellite during transmissions from Fort Richardson are shown in Figure 12. A signal could be detected on 60% of all possible passes over Lauder, New Zealand telemetry station. The data in Figure 12 shows a near continuum of both negative and positive Doppler shifts from a fixed transmission frequency of 13.275 kHz. The Doppler signatures can be reproduced by ray tracing whistler-mode waves through the magnetosphere (Ref. 11).

Spectrograms of the transmitter signal received by the S3-3 satellite over Alaska during transmissions from Naseby, New Zealand are shown in Figure 13.

The direct signal from the TVLF transmissions from the high-latitude site at Kafjord, Norway have not been positively identified in the data from the VLF receiver aboard the high-altitude SCATHA (P78-2) satellite. However a variety of plasma wave emissions were stimulated or modified at the frequency of the transmissions (Ref. 12). An emission stimulated by the transmitter is shown in Figure 14.

The magnetospheric-wave injection experiments performed at a variety of latitudes and frequencies have provided data used to assess the properties of the magnetosphere as a communications medium at VLF and to assess the importance of power line radiation as a disturbing influence in the outer magnetosphere. The data have also been used to increase understanding of the nonlinear interaction between whistler-mode waves and energetic electrons.

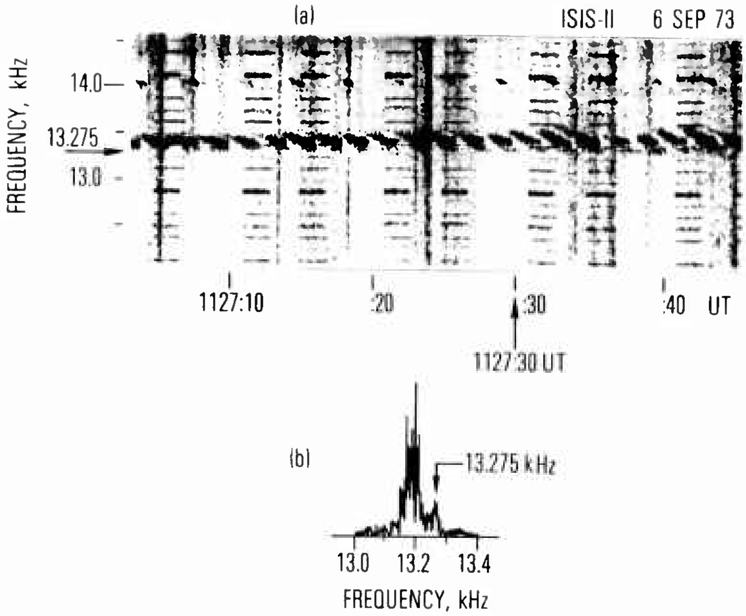

Figure 12. Spectrograms of VLF signals received by ISIS-2 satellite during transmission from Fort Richardson, Alaska. (a) Doppler shifts observed by the ISIS 2 satellite VLF receiver. The ground-based transmitter was located at L ~ 4 in Alaska, and the satellite was over New Zealand. The transmitter was operating at 13.275 kHz as part of a VLF magnetospheric transmission experiment conducted by The Aerospace Corporation and the University of Otago in New Zealand. The transmitter was repeatedly keyed on for 1 s and off for 1 s during this time segment. Maximum negative Doppler shifts observed in the above figure range from 100 to 200 Hz. (b) Amplitude scan of a pulse at 1127:30. The vertical scale is linear but arbitrary. There are approximately seven signals separated by 10-20 Hz in the Doppler envelope. There is also a signal with no Doppler shift at the carrier frequency.

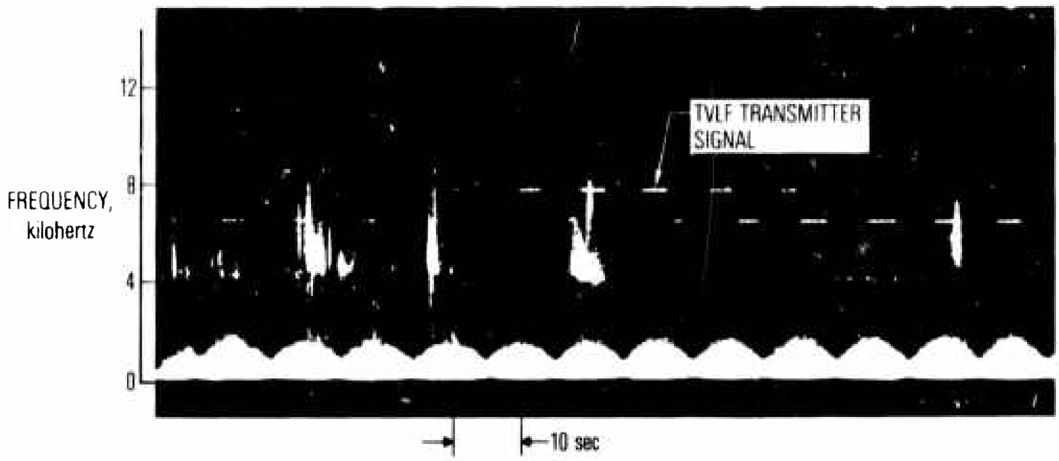

Figure 13. TVLF transmitter signals detected by the S3-3 satellite VLF receiver. The transmitter was located at L ~ 2.9 in New Zealand, and the satellite was over Alaska. The transmitter was frequency shift keying between two frequencies.

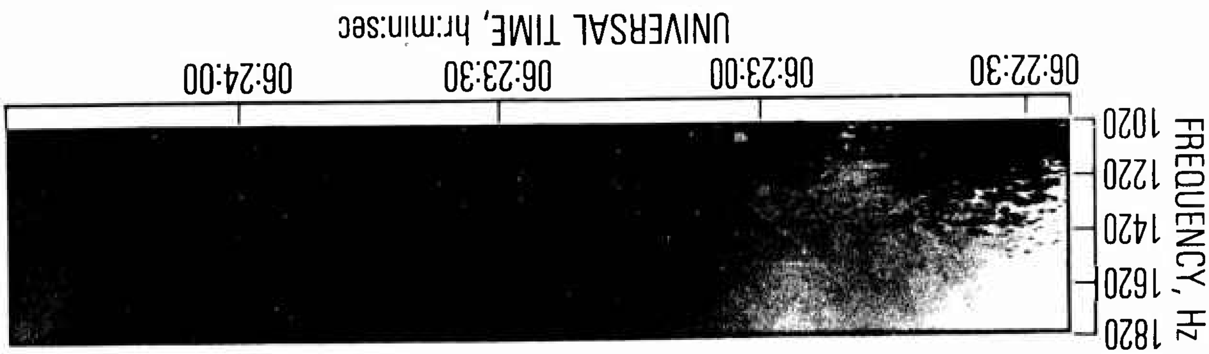

Figure 14. ELF emission detected by the SCATHA (P78-2) satellite VLF receiver at 1420 Hz shortly after the TVLF transmitter began transmissions at 1420 Hz.

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SUPPLEMENTARY

INFORMATION

THE AEROSPACE CORPORATION

DOCUMENT CHANGE NOTICE

TO: Holders of "High-Power Transportable VLF Transmitter Facility" Report TR-0082(2940-06)-2 (SD-TR-82-31)

DATE: 26 August 1982

SUBJECT: Errata to Figure 6.

FROM: Mitchell H. Dazey
Harry C. Koons

AD-A117419

Please replace Figure 6, Page 34, with the attached change page.

AEROSPACE FORM 4518

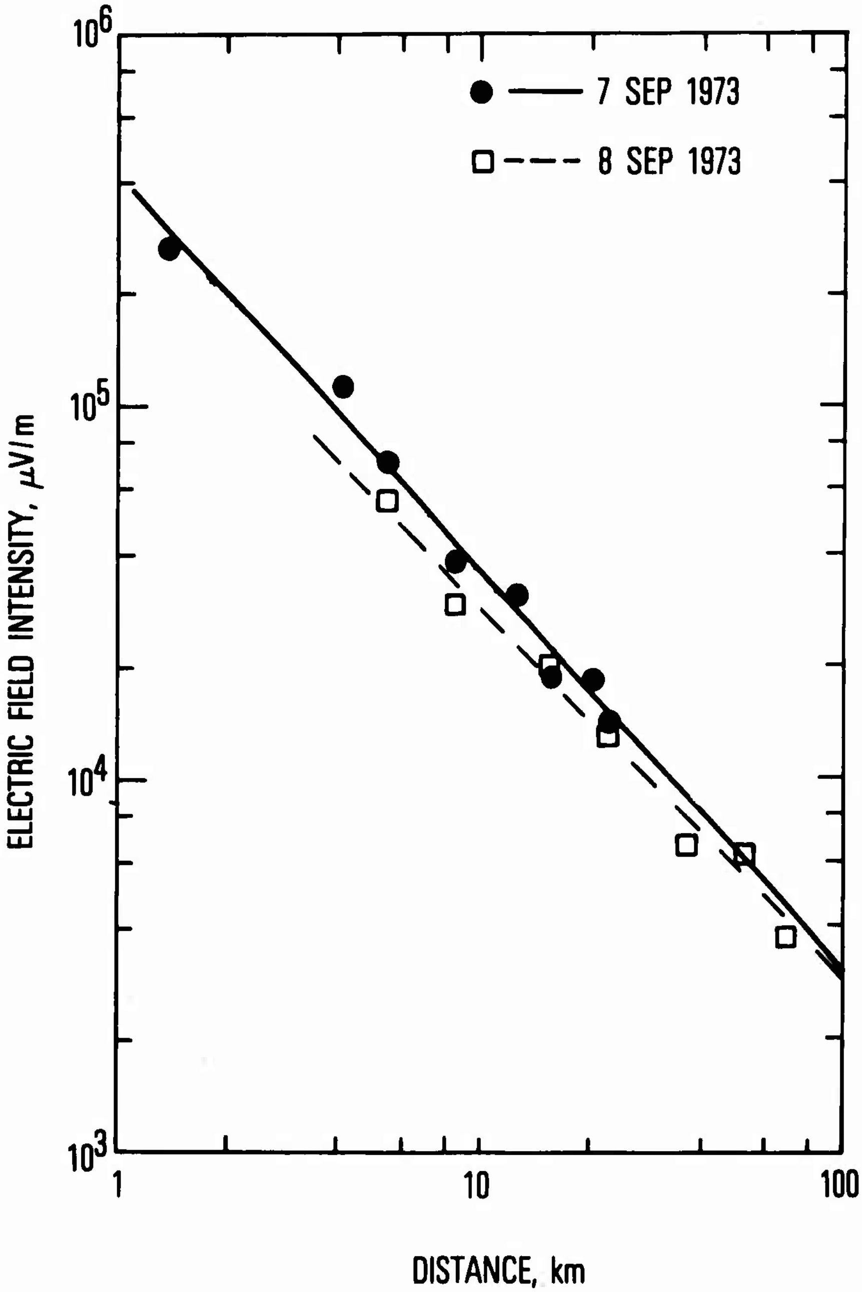

Figure 6. The electric field intensity as a function of distance from the balloon lofted antenna during operations at 13.275 kHz with a base current of 36.6 A.

SUPPLEMENTARY

INFORMATION

AD-A117419

THE AEROSPACE CORPORATION

DOCUMENT CHANGE NOTICE

TO: Holders of "High-Power Transportable VLF Transmitter Facility" Report TR-0082(2940-06)-2 (SD-TR-82-31)

DATE: 14 September 1982

SUBJECT: Errata to Figure 6.

FROM: Mitchell H. Dazey
Harry C. Koons

The Y-axis and the figure title are labeled incorrectly on Figure 6, page 34. Please replace pages 33 and 34 with the attached change page.

base current and winch capacity current. The winch capacity causes a reduction of about 3.4 A in the antenna current for the example we are considering. The antenna current would then be 36.6 A.

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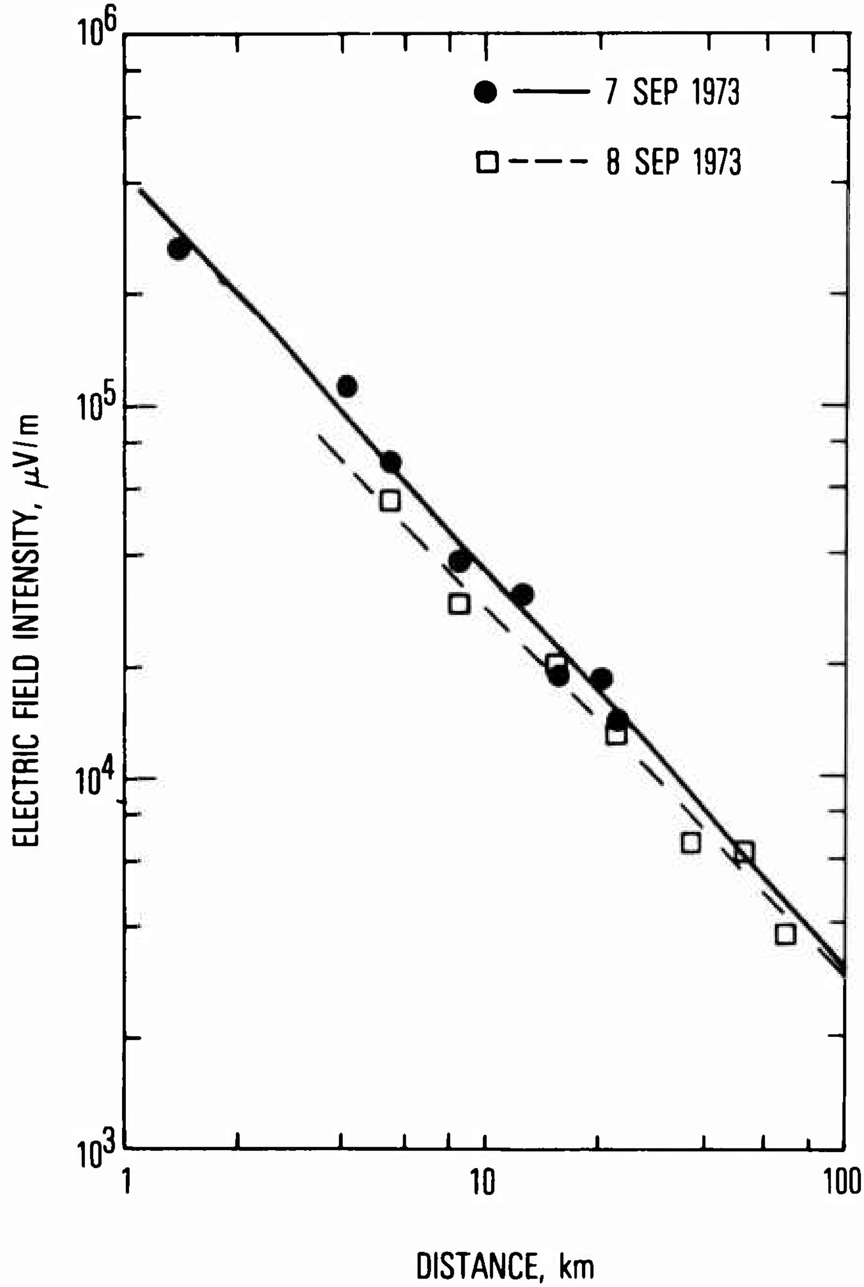

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